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Semi-Annual Status Report #2

NASA Grant NAG 5-495

Coordinated Observations of

X-Ray Bright BL Lacertae Objects

C. Megan Urry, Principal Investigator

15 September 1985 - 15 March 1986

This is a semi-annual status report to the National Aeronautics and Space Administration (NASA) concerning NASA grant NAG 5-495. This grant was awarded to Dr. C. Megan Urry of the Massachusetts Institute of Technology in response to a proposal, entitled Coordinated Observations of X-Ray Bright BL Lacertae Objects, to use the International Ultraviolet Explorer (IUE) satellite. The grant was awarded on 3/15/85; this report covers the second six months of its duration, or September 15, 1985 through March 15, 1986.

No new IUE observations were scheduled as part of our program during this time period. As a result there were no trips to Goddard Space Flight Center, and thus no major expenditures of funds from grant NAG 5-495. However, activities related to previous IUE observations continued, and these are described below.

I continued to work with the staff of the IUE Regional Data Analysis Facility (RDAF) at Goddard on the new spectral extraction routine. The computer code was adapted from the RDAF PDP 11/44 computer to a VAX 11/750, in order that it run more quickly. I am collaborating with at least one IUE user, Dr. D. Hutter of the Applied Research Corporation, who is undertaking an archival study of the ultraviolet spectra of BL Lacertae objects. Some tests using the programs were undertaken using the RDAF remotely (via long-distance phone connection).

I was invited to collaborate on a chapter on ultraviolet observations of blazars for a book celebrating the scientific accomplishments of IUE. During the first part of 1986, I worked on my contribution to the chapter, which was being coordinated by Dr. J. Bregman of the National Radio Astronomy Observatory, with the assistance of Dr. L. Maraschi, of the University of Milan, and myself. A copy of the final draft is attached to this report. Several overnight package delivery services were used in order to expedite communication at a number of junctures. These are the only expenditures of NAG 5-495 during the period September 15, 1985 through March 15, 1986.

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Because of the lack of scheduled observations, and the relative lack of time for data analysis and reduction, several of the objectives of this IUE program were not met as of March 15, 1986. Thus I applied for a no-cost extension of this grant, which would otherwise have expired. NASA granted this extension, and continued the grant until September, 1986.

This concludes the second semi-annual status report on NASA grant NAG 5-495. Total direct expenditures for the grant during this period were less than $30 dollars.

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Ultraviolet Observations of Blazars

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(to appear in the book "Scientific Accomplishments of the IUE")

[1] National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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In view of observations at other wavebands and theoretical models, the ultraviolet region is of critical importance. It is where the continuum is expected to change from being dominated by synchrotron radiation to being dominated by inverse Compton radiation. Synchrotron loss processes are more severe in the ultraviolet than in the optical-infrared regions and evidence of such losses contains independent information about magnetic fields and energy densities. The ultraviolet region is also the highest frequency at which these sources could be observed regularly for several years. Not a single blazar had been studied in the ultraviolet prior to the launch of the International Ultraviolet Explorer. Here we summarize a variety of vigorous programs carried out during the past eight years on the IUE that are aimed at developing a deeper understanding of the continuum properties in this volatile class of objects.

II. Ultraviolet Spectra Of The Blazar Class

The blazar class has been discussed most recently by Angel and Stockman (1980), who listed all known objects that met the criteria of variability, polarization, and flux properties. Sources meeting their selection criteria that have been observed by the IUE are summarized in Table 1. In keeping with these criteria, NGC 1275 has been included, although it is considered in more detail elsewhere in this volume. Four additional blazars that were discovered since 1980 have been included: H 0323+022, 0716+71, H 1218+304, and PKS 2005-489. The data in Table 1 are based upon information either published or brought to our knowledge before February 1986 and includes the results of a systematic search of the data archives up to December 1983, which were partially published in Maraschi, Tanzi, and Treves (1984), Treves et al. (1986), and Ghisellini et al (1986).

In Table 1, the coordinate designation and names of the objects are given in columns 1,2, the redshift is listed in column 3 as is an associated letter that indicates how the redshift was determined. Redshifts derived from an underlying galaxy is designated by "g", while "w" and "s" indicate the presence of weak or strong emission lines; redshifts determined from absorption lines are given as lower limits. The flux densities at 2500 A and 1500 A (columns 4,5) have been dereddened with the value of A_V (column 7) according to the ultraviolet extinction law of Seaton (1980); minimum and maximum fluxes are listed for sources in which variability was detected. The

spectral index α ($F_{\nu} \propto \nu^{-\alpha}$; column 6) was usually determined by a power law fit to the combined long and short wavelength spectra. This procedure ignores the possibility of curvature of the spectrum and of rapid variability (shorter than a day). However, in our experience, it gives a more reliable estimate of the spectral shape than individual fits to each wavelength range. The resulting errors, ignoring extinction uncertainties, are, for reasonably exposed spectra, of the order of 10% in α. Sources with faint spectra or lacking exposures with both cameras have poorly determined slopes (± 50%) and are indicated as such in Table 1. References and comments are reported in column 8.

a) Ultraviolet Spectral Slope Of Blazars And Comparison With Other Classes Of Objects

An advantage of using the IUE to determine continuum slopes is that the ultraviolet waveband is practically free from contamination by starlight from the underlying galaxy. However, an important selection effect should be mentioned about the observation of blazars. Because these sources are among the faintest objects observed with the IUE, it is likely that blazars known to have an especially steep optical spectrum were not chosen for study with the IUE (for fear of nondetections). Consequently, many sources that might have especially steep ultraviolet spectrum were never observed, so the distribution of spectral slopes reported in Figure 1 is probably deficient for $\alpha > 2$. Therefore, $\langle\alpha\rangle = 1.4$ is less than what would have been determined if a complete sample of blazars could have been

observed. Nevertheless, the mean slope is still substantially greater than that found for quasars by Richstone and Schmidt (1980), who derived a mean spectral index of 0.6 at 2500 A in the rest frame. Much of the dispersion (and the flatness) in the spectral indices of quasars found by Richstone and Schmidt probably arises from the presence of a blue bump component and it has been claimed that the underlying power law index is remarkably constant at about 1.1 (Malkan and Sargent 1982; Elvis 1985). The blue bump component is far less important in blazars (and frequently not present; see § III), so the considerable dispersion of the spectral index in blazars probably carries direct information about the underlying electron population or about the spectral shift of a spectrum for which Doppler boosting is important.

An interesting point concerns the X-ray selected blazars. We define a sample of sources appearing above the completeness limit of the X-ray catalogues of Piccinotti et al. (1982) and Wood et al. (1984), which cover a large fraction of the sky. Six sources in Table 1 satisfy this criterion: H 0323+022, PKS 0548-322, Mkn 421, H 1218+304, Mkn 501, and PKS 2155-304. Ultraviolet spectral indices less than 1.0 have been seen in only six objects, four of which are in this subsample. In fact, the mean ultraviolet spectral index of this subsample is 0.9, which is significantly flatter than the average for the whole group. The association of the strong X-ray emission with the flat ultraviolet spectrum is suggestive of a connection between the

two spectral domains (e.g., a common emission mechanism). A deeper examination of this connection for the entire sample is given below (§III).

b) Ultraviolet Variability

Several of the 33 blazars listed in Table 1 have been observed repeatedly and in at least 11 cases, the flux density was found to vary by more than 50% and in some cases, greater than an order of magnitude (1156+295, Mkn 421, 3C 446, OJ 287). However, it is impossible to determine quantitatively the frequency with which ultraviolet flares occur because many of the objects were chosen for study based upon their degree of optical variability just prior to IUE observations. The shortest spacing between IUE observations is generally a day or longer; few observations address the issue of variation during a single day (the exposure times themselves are 2-8 hr). Given these limitations, the timescale of variability for ultraviolet emission appears to be approximately the same as for optical variation. Changes on a timescale of a day are rare but have been observed while variability with a timescale of a week or greater is more common.

Variation in the ultraviolet spectral slope has also been detected but is rarely, if ever large. Even when the intensity variation is great, the spectral index varies by less than 0.5. No strong correlation exists between the intensity level and spectral slope, although weak trends were found for a few cases in which the spectrum hardens as the source brightens (Mkn 421, Ulrich et al. 1984; OJ 287, Maraschi et al. 1986; Fig. 2). This

flux - spectrum correlation, which is barely evident in blazars, is well defined in Seyfert galaxies (Perola et al. 1982; Bari, Willis, and Wilson 1983)

c) Ultraviolet Emission Line Characteristics

Emission lines provide an unambiguous measurement of the velocity of thermal gas for the inner few parsecs and they contain important information about the ionizing continuum. Since the ionizing continuum of BL Lacertae objects is indistinguishable from that of violently variable quasars, both classes of sources have sufficient ionizing radiation to create emission lines (provided that the emission line gas sees the same ionizing continuum as we). It has been suggested that BL Lacertae objects might have emission lines, but the line ratios would be considerably different from quasars and that only the highest ionization lines, such as O VI λ 1035 A, would be visible (Krolik, McKee, and Tarter 1978). No ultraviolet emission lines have been detected in any of the BL Lacertae objects observed, with upper limits to the equivalent widths of about 10A.

Several objects on Angel and Stockman's list with known optical emission lines were observed with the IUE. The source with the largest equivalent width broad lines is 3C 390.3, which is one of the only blazars that is a broad line radio galaxy. However, nearly all other blazars may be characterized as having smaller equivalent widths for the broad emission lines than normal quasars. This result occurs partly because many of these objects were chosen for observation when the continuum was

bright, so that the broad lines, which do not vary in most sources, appear washed out and have small equivalent widths. Of greater importance is the steepness of the continuum in reducing the equivalent width of the lines. Rather than compare equivalent widths, it may be more significant to calculate the covering factor of the broad line clouds, which is the fraction of ionizing photons that should be absorbed in order to account for the Lα line strength. The covering factors for the violently variable quasars PKS 0521-36, 3C 446, and 3C 345 are similar to the ordinary quasars observed by Richstone and Schmidt, by Kinney et al. (1985), and by Bregman et al. (1986a,b). Consequently, the strengths of the broad lines in these objects are about "normal" for the number of ionizing photons available.

The presence of narrow lines depends upon the host galaxy and whether or not the object is nearby. Weak narrow emission lines are seen in 3C 371, which is a low redshift N galaxy with interesting absorption lines but no broad emission lines (Miller 1975; Worrall et al 1984).

Of special interest is 3C 446, the only high luminosity OVV in which broad emission line variability has been seen, both in the optical and the ultraviolet (Stephens and Miller 1985; Bregman et al. 1986b). The line and continuum fluxes usually change together, thereby maintaining constant equivalent width. The timescale for variability of Lα is two months (rest frame). Because the distance of the broad line region from the ionizing source as deduced from ionization and luminosity considerations

is about a light decade, the broad emission line gas was inferred to be distributed asymmetrically about the central source. Much of the broad line gas must lie close to our line of sight on the near side of the quasar.

III. The Connection of the Ultraviolet Spectra to Spectra at Other Frequencies

a) Single Epoch Multifrequency Spectra

Because of the rapid variability in the flux density of these objects in all observable wavebands, the connection between the ultraviolet emission and that in other spectral regions requires simultaneous observations (i.e., taken over a time period less than the shortest variability timescale, which is a day to a few weeks, depending upon the particular source). Although the ability to obtain high quality optical, near infrared and radio data existed prior to the launch of the IUE, sensitive X-ray, far infrared and submillimeter measurements became available only during the lifetime of the IUE. Despite the difficulties of assembling large observing teams and coordinating many observatories, some of them space-based, several independent programs were undertaken to obtain single epoch spectra spanning almost ten decades in frequency. Two dozen BL Lacs and OVVs were observed in these programs, many of them more than once (Table 1). Additional data from ground-based observations alone, spanning a smaller frequency range, have also been obtained for other sources.

The multifrequency spectra of blazars, which are listed in Table 1, has some striking similarities. The radio spectra are flat or rising in the 10^8 - 10^{10} Hz region, probably due to a superposition of components that become optically thick at different frequencies. In the 1 mm - 60 μm region, the spectrum

steepens and may be characterized by a power law of index 0.6 to 1.4 in the infrared and near infrared regions. Between the infrared and the ultraviolet regions, spectral steepening occurs (mean change in slope of 0.5), the magnitude of which varies considerably in the current sample. For example, 0235+164, BL Lacertae, and 3C 446 have spectra that steepen exponentially between the infrared and ultraviolet regions. This dramatic spectral steepening, which occurs at a few microns in the class of objects known as red quasars, is probably a common phenomenon that can occur in the infrared through X-ray range (Rieke, Lebofsky, and Wisniewski 1982). This spectral behavior has been interpreted as resulting from an abrupt cutoff in the underlying electron spectrum (Beichman et al. 1981; Bregman et al. 1981) associated with the difficulties of accelerating particles above a specific energy. In these sources the spectral steepening is determined by the high frequency tail of the single electron emission function rather than by the detailed shape in the cutoff of the electron spectrum.

Less dramatic spectral softening that occurs over decades of frequency space may reflect changes in the actual shape of the underlying electron spectrum, complex mass motions or nonhomogeneous emitting regions.

The connection between the ultraviolet and X-ray emission is sometimes investigated by determining whether the ultraviolet continuum extrapolates smoothly to the X-ray data. In doing so, we bear in mind that most X-ray observations were not

simultaneous with the ultraviolet measurements. If this extrapolation is carried out assuming that the continuum does not steepen between the ultraviolet and X-ray region, the extrapolation passes at least a factor of two below the X-ray flux in about 40% of the sources in Table 1. This calculation was also performed by permitting spectral curvature between the ultraviolet and X-ray region, where the adopted spectral curvature is determined by the difference in the infrared and ultraviolet slopes (i.e., constant curvature for the infrared through X-ray region as defined in a log F_ν, log ν plot). The extrapolation falls at least a factor of two below the X-ray flux in about 65% of the objects. In these cases, the X-ray flux is probably produced by a different mechanism than the ultraviolet emission or it arises in a different spatial location. Of the sources for which an extrapolation of the ultraviolet continuum passes through or above the X-ray flux, most are either X-ray or optically selected objects, even though these are a minority of the entire sample (PKS 0548-322, Mkn 421, Mkn 180, 1218+304, Ap Lib, Mkn 501, IZw-187, 2155-304). These are the "X-ray strong blazars" discussed by Ledden and O'Dell (1985) or the "radio weak blazars" discussed by Maraschi et al. (1986). Ultraviolet and multifrequency data suggest that for these sources, the X-ray emission may be a high frequency extension of the synchrotron emission that produces the ultraviolet, optical, and infrared emission. Studies of the X-ray spectra reveal that PKS 2155-304, 0548-322, Mrk 501, Mrk 421, and 1218+304 have steep soft X-ray

spectral slopes that flatten at higher energies (Urry and Mushotzky 1982; Urry 1984, 1986; Singh and Garmire 1985, Morini et al. 1986; Makino et al. 1986, Brodie et al. 1986). This may be understood as steepening of the synchrotron emission in the soft X-ray region and the dominance of another emission process, such as inverse Compton radiation at higher energies.

The relation in the continuum properties of blazars is in contrast to the situation for ordinary quasars, where the ultraviolet spectrum is considerably harder and a similar extrapolation passes well above the X-ray emission. In ordinary quasars, the blue bump makes an important contribution to the ultraviolet continuum. For the BL Lacertae objects, no blue bump has ever been unambiguously identified (the blue bump reported in IZw-187 by Bregman et al. 1982a was not confirmed in subsequent observations). In some of the violently variable quasars, such as 3C 345, a blue bump is seen, but it is fairly weak and does not lead to the hard ultraviolet spectrum seen in ordinary quasars (Bregman et al. 1986a). In other objects, such as 3C390.3 where the broad line strength is considerable, the blue bump appears to be stronger (Oke, Shields, and Korycansky 1984). This suggests that the presence and strength of a blue bump is directly related to the strength of the broad emission lines.

For nearly all of the radio selected blazars, the primary contribution to the observed power generally comes from the submillimeter through optical region (assuming either isotropic emission or similar beaming of all components), with the

contributions from the radio, ultraviolet, and X-ray regions being at least several times smaller (Fig. 3). In contrast, most of the X-ray and optically selected blazars have their peak power per logarithmic bandwidth in the ultraviolet and X-ray region (Fig. 3).

b) Variability In Other Wavebands Compared To Ultraviolet Activity

A comparison of the variation in the flux density at ultraviolet wavelengths with that at other wavebands is a particularly powerful method of probing the physical connection between the spectral regions. Unfortunately, this requires a considerable effort by a number of observers and has been carried out for only a fraction of the blazar sample (Table 1).

Flux variations in the optical and infrared regions are generally correlated with those in the ultraviolet, but the variation in the two regions is not always identical. Flux density variations in which the shape of the spectrum is preserved in infrared-optical through ultraviolet regions have been seen in 3C 371, 3C 66A, 0735+178, 3C 446, and OJ 287 (Worrall et al. 1984a,b; Bregman et al. 1984; Bregman et al. 1986c). This was also the case for 1156+295 (Glassgold et al. 1983), in which a sequence of observations was made near and immediately after the peak intensity of a particularly violent outburst (Fig. 4). No pronounced spectral variation occurred as the source dimmed, although some separate infrared data showed modest but temporary steepening. In some of the sources,

spectral variation has occasionally been seen (3C 371, 0735+178, 3C 345; Worrall et al. 1984; Bregman et al. 1984; Bregman et al. 1986a). The sense of the variation is that the ultraviolet emission often (but not always) shows greater change than optical or infrared emission. In the X-ray bright sources, the X-ray variation is often greater and more rapid than at lower frequencies. Despite these few cases, the data are too sparse to determine in general whether the spectrum of a source softens or hardens during brightness variations.

The connection of the ultraviolet variability to that in the radio and submillimeter wavelengths is less direct. Radio variability is clearly not directly connected to the ultraviolet brightness since there are several examples in which variation is seen in only one waveband (usually the ultraviolet) or variations in both wavebands occur but in the opposite sense (3C 371, 0735+178, 3C 446; Worrall et al. 1984, Bregman et al. 1984, 1986c). It is tempting to expect that variability in the ultraviolet is connected to that in the radio through a common emission process (synchrotron radiation), but that this connection is obscured by time delays, energy losses, or particle acceleration. A connection between optical and radio outbursts has been found from long term monitoring data for OJ 287 (Pomphrey et al. 1976, Balonek 1982), AO 0235+164 (Balonek and Dent 1980), 3C 345 (Balonek 1982, Bregman et al. 1986a), and is suspected for several other blazars (Balonek 1982). This decade old finding for OJ 287 was recently reaffirmed during the 1983

outburst in which the source was highly variable from the radio through the ultraviolet band at the same time (Holmes et al. 1984, Moles et al. 1984, Aller et al. 1985, Maraschi et al. 1986).

A comparison between the ultraviolet and X-ray variability displays an unusually broad range of behavior. The ultraviolet emission from 0735+178 increased by nearly a factor of four in observations separated by a year, but simultaneous X-ray observations failed to show any increase (Bregman et al. 1984; the systematic uncertainties in the absolute flux of Einstein IPC measurements are about 20%). The subsequent decrease in the ultraviolet brightness over a year was also unaccompanied by any change in the X-ray emission. Only modest radio variability occurred during this time, which is consistent with the limits on the X-ray variation and led to the suggestion that the soft X-ray emission and the radio emission may be linked through inverse Compton scattering of radio photons (the difference between the optical-ultraviolet and the X-ray emission is supported by at least one multifrequency spectrum in which an extrapolation of the ultraviolet continuum passes below the X-ray datum).

In several other sources, the ultraviolet and X-ray emission tends to be more closely related. In Mkn 421, a modest decrease in the both the ultraviolet and X-ray flux were seen in widely separated observations (1978 and 1984; Pounds 1985). Makino et al. (1986) have recently completed an intensive study of Mkn 421 and find that the ultraviolet, optical, and infrared fluxes

decreased by about 20-30% in five weeks while the radio flux remained unchanged (to within 7%) and the X-ray flux decreased by a factor of about two. A similar behavior was found for PKS 2155-304 (Morini et al. 1985, 1986). In both cases, the change in the hard X-ray band was greater than in the soft X-ray band, which could arise from an inhomogeneous emitting region or from distinct components. In contrast is the behavior of 3C 446, where the ultraviolet, optical, and X-ray emission decreased together while slower, less dramatic dimming occurred at radio frequencies (Fig. 5; Bregman et al. 1986c). Similar, but less well documented variability is seen in OJ 287 (Pollock et al. 1985) and PKS 0537-441 (Tanzi et al. 1986), but an especially perplexing source is 1156+295 (McHardy et al. 1986). In 1156+295, a well resolved X-ray outburst occurred between two optical outbursts that were separated by a few months; it is ambiguous which optical outburst (if any) the X-ray outburst is associated with.

The wide variety of X-ray variation when compared to the emission at ultraviolet and other wavelengths suggests that there may be more than one X-ray emission process or more than one X-ray emission region. The X-ray emission (particularly in bright sources) may be explained as an extension of the ultraviolet synchrotron emission (e.g. Mkn 421). This may be the case for optically and X-ray selected blazars in general (Ledden and O'Dell 1985). However, this picture cannot explain the behavior of 3C 446, in which an extrapolation of the steep ultraviolet

spectrum passes orders of magnitude below the X-ray emission. In cases such as this, the X-ray emission is likely to arise from the inverse Compton process in which the scattering occurs in the infrared-ultraviolet emission region. The likely explanation for the X-ray emission in 0735+178 is that it arises from inverse Compton scattering that occurs in the radio emission region (Bregman et al. 1984).

IV. Theoretical Considerations

Synchrotron emission is the dominant process in the radio through ultraviolet region, while the X-ray emission probably arises from either the synchrotron or the inverse Compton process. These processes have been combined into a synchrotron self-Compton model, in which relativistic plasma produces emission at radio through ultraviolet frequencies via the synchrotron process while some of these photons are inverse Compton scattered by the plasma to X-ray frequencies (e.g. Jones, O'Dell, and Stein 1974). Through VLBI constraints and radio flux variability, it was recognized that the emitting plasma might have relativistic bulk motion, with Lorentz factors of a few. The interpretation of flat radio spectra as a superposition of partly opaque components (Condon and Dressel 1973; Marscher 1977) and VLBI studies that show the source size changing with frequency (e.g. Cotton et al. 1980) have led to models with non-homogeneous plasma, often in a jet-like geometry (Blandford and Konigl 1979; Marscher 1980; Konigl 1981; Reynolds 1982; Ghisellini et al. 1985; Hutter and Mufson 1986). In these jet models, the electron density and magnetic field decrease with distance along the jet. The geometry and velocity structure of the jet is either assumed or calculated from some adopted hydromagnetic model. Although there are too few observational diagnostics to make a unique model selection, a range of parameters can be usefully calculated.

The application of jet models to the data leads to the

following typical values for the physical conditions in the plasma responsible for the far infrared through ultraviolet emission: magnetic fields that of 10^{-2} - 10^{2} G, particle densities of 10^{2} - 10^{6} cm^{-3}, and sizes of light days to light months. Calculations of the Doppler boosting factor depend upon assumptions about how variability timescales translate into physical sizes and whether the timescale for electrons to lose their radiation contains information about the source size. Estimates for the boosting factor range from unity in several cases (no relativistic bulk motion required) to > 10, but most sources have values of 2-5. It is interesting that in a few sources, the energy density in particles, magnetic fields, and photons are comparable in the far infrared through ultraviolet emitting region.

V. Summary and Conclusions

The 33 blazars that have been observed with the IUE since launch have permitted investigators to carry out detailed line and continuum studies. The observations indicate that the lack of broad emission lines in BL Lacertae objects is not due to the absence of ionizing photons. Either sufficient gas is not present, or the ionizing flux we observe is not incident upon the gas clouds. The broad emission lines in violently variable quasars have small equivalent widths when compared to normal quasars, but the line fluxes are nearly normal for the number of ionizing photons (the covering factor is nearly normal). In 3C 446, variation of Lα in two months implies that considerable broad emission line gas lies along our line of sight and on the near side of 3C 446.

The ultraviolet continuum emission from blazars is nearly always steeper than the optical and infrared continuum. Ultraviolet slopes range from 0.5 to 3, with a mean of 1.4, which is significantly steeper than the mean slope of ordinary quasars, 0.6. In several sources, the ultraviolet flux density decreased by more than an order of magnitude in observations separated by months or more while variation of a factor of four was seen in observations of 1156+295 that were separated by four days. Only modest ultraviolet slope variation has ever been observed ($\Delta \alpha$ < 0.5), and there is little, if any correlation between spectral slope variation and flux density. The observed variability seems to be similar to, if not identical to, variation at optical and

infrared wavelengths. This is not generally true when the comparison is made with X-ray variations. Changes in the X-ray flux are often faster and more dramatic than in the ultraviolet waveband. Such changes are sometimes well correlated with ultraviolet and optical variation, but there are cases where the ultraviolet emission varies while the X-ray emission does not and cases where the X-ray emission variation is unaccompanied by similar behavior at ultraviolet frequencies. This suggests that in some sources the X-ray emission may be produced by a different process or in a different spatial region than the ultraviolet emission.

Multifrequency spectra reveal that the nearly universal flat radio spectrum steepens in the millimeter or submillimeter region and there is a smooth connection between the infrared, optical, and ultraviolet regions. Along with the variability data, this suggests that the ultraviolet radiation, like the infrared and optical emission, is produced by the synchrotron process. In one extreme type of source (BL Lac and 3C 446), the optical and ultraviolet continua steepen extremely rapidly with increasing frequency so that they resemble Red Quasars. Because an extrapolation of the ultraviolet continuum to higher frequencies passes orders of magnitude below the X-ray flux, the X-ray emission may be produced by the inverse Compton mechanism. Although spectral steepening is less dramatic in most blazars, a similar separation between the ultraviolet and X-ray emission exists for about half or more of the sources. At the other

extreme, objects such as Mkn 421 and 2155-304 have hard ultraviolet spectra, modest spectral steepening, and an extrapolation of the ultraviolet continuum would connect smoothly to the soft X-ray flux; synchrotron emission probably produces the X-ray emission. A high proportion of sources with this behavior were either X-ray or optically selected.

It is encouraging that multifrequency data provide enough information for use in non-homogeneous synchrotron-self-Compton models. Although there is some latitude in the choice of models, typical physical properties of the plasma emitting the far infrared through ultraviolet emission is: 10^{-2} - 10^{2} G, densities of 10^{2} - 10^{6} cm^{-3}, sizes of light days to light months, and Doppler boosting factors between unity (no relativistic bulk motion) and 10.

Although tremendous progress in our understanding of blazars has been achieved, neither the complex connection between the ultraviolet and the X-ray region nor the detailed structure of the emitting plasma is fully understood. One powerful tool in unraveling these issues is through multiwavelength variability, and a few such studies have already added considerably to our understanding (§IIIb). Improved model predictions and a more ambitious program of multifrequency variability with better time coverage and for more sources may permit the emitting plasma to be mapped spatially and provide us with a deeper understanding of the structure of the emitting plasma.

Ultraviolet Data for Blazars

Table 1

Object	Name	z	$F_\nu(2500)$	$F_\nu(1500)$	α	A_V	Reference - Comments
0215+015		>1.686	0.7	-	-	-	Blades et al. 1985; mup
0219+428	3C66A	0.44 w	1.3	0.57	1.6	0.15	Maccagni et al. 1983
							Worrall et al. 1984c[m]
0235+164	AO	>0.852	0.1	-	-	-	Snijders et al. 1982
0316+41	NGC1275	0.0172	3.8	1.9	1.6	0.6	Maraschi et al. 1984
0323+022	H	~0.13 g	0.3	0.1	1.4	-	Feigelson et al. 1986[m]
0521-365	PKS	0.055 w	0.36	0.16	1.5	-	Danziger et al. 1983
			0.25	0.1	1.5	-	Ulrich et al. 1984
0537-441	PKS	0.894 w	1-2	-	1.5	0.2	Maraschi et al. 1985[m]
0548-322	H	0.069 g		0.3	0.8	-	Urry et al. 1982; mup
0716+71		-	0.17	0.1	1	-	Frichi et al. 1981
							Maraschi et al. 1984
0735+178	PKS	>0.424 s	0.8	0.3-1.5	1.8-1.5	0.15	Bregman et al. 1981,1984[m]
0736+017		0.191 s	0.63	0.35	1	0.3	
0754+10	OI90.4	-	1.5	0.7	1.5	-	Worrall et al. 1984c[m]
			1	0.35	2.1	-	
0829+046	OJ049	-	1.7	0.6	2.1		Maraschi et al. 1984; mup
0851+202	OJ287	0.306 w	0.8	0.35	1.8	0.1	Worrall et al. 1982[m]
			5	2.8	1.2	-	Maraschi et al. 1986
0912+297	OK222	-	1	0.5	1.5		Worrall et al. 1986[m]
1101+384	Mkn421	0.0308 g	3.6	2.2	1.2		Ulrich et al. 1984; mup
			12.1	8.7	0.75.		
1133+704	Mkn180	0.046	0.61	0.42	0.7	-	Mufson et al. 1984[m]
1156+295	TON599	0.729 s	0.75	0.3	1.7		Glassgold et al. 1983[m]
			4.5	1.7			
1215+303	ON325		-	0.6	1		Worrall et al. 1984b[m]
1219+305	2A	~0.13 g	0.6	0.4	0.64		Urry et al. 1984

Object	Name	z	$F_\nu(2500)$	$F_\nu(1500)$	α	A_V	Reference - Comments
1219+285	ON231	0.102 g	0.7	0.3	1.7		Worrall et al. 1986[m]
1308+32	B2	0.996 s	0.5	-	0.7		Maraschi et al. 1984; mup
1418+54	OQ530	-	0.53	0.21	1.8		Worrall et al. 1984b[m]
1514-24	APLib	0.049 w	1.9	-	2	0.2	
1641+399	3C345	0.585 s	0.9-1.5	0.4-0.75	1.3-1.8		Bregman et al. 1986b[m]
1652+398	Mk501	0.0337 g	1.8-2.6	0.9-1.3	0.7-1.1		Snijders et al. 1979 Kondo et al. 1981[m] Mufson et al. 1984[m]
1727+502	IZw187	0.0554 g	0.32	0.2	1		Bregman et al. 1982a[m]
1807+698	3C371	0.05 w	1.7	0.7	1.7	0.13	Worrall et al. 1984a[m]
1845+797	3C390.3	0.056 s	0.7	0.4	1.2	0.3	Ferland et al. 1979 Oke and Goodrich 1981
2005-489	PKS	-	6.3	3.5	1.4		Wall et al. 1986
2155-304	PKS	0.118 g	4.5-11	8.7-1.7	1.2-0.7		Maraschi et al. 1986; mup
2200+420	BLLAC	0.069 w	1.5	-	3	1	Bregman et al. 1982b[m]
2223+056	3C446	1.404 s	0.1-0.7	-	3	0.15	Bregman et al. 1986a,c[m] Brown et al. 1986 Garilli and Tagliaferri 1986

m denotes multifrequency spectrum

mup indicates that multifrequency data exist but are unpublished

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Figure Captions

Fig. 1. Distribution of spectral indices of blazars observed in the ultraviolet. In cases of observed spectral variability, the arithmetic mean between maximum and minimum values has been used. The mean slope, 1.4 is greater than the value of 0.6 found for normal quasars.

Fig. 2. The distribution of spectral index and flux for PKS 2155-305 during 1978-81 (Urry et al. 1986). No apparent trend is evident. Slopes determined after 1982 (not shown) tend to be steeper and fainter than during 1978-82 (Maraschi et al. 1986).

Fig. 3. The power per logarithmic bandwidth for Mrk 421 (Makino et al. 1986) and 3C 446 (Bregman et al. 1986c). For 3C 446, most of the observed power emerges in the far infrared through optical region while for Mrk 421, most of the observed power emerges near the ultraviolet region. For Mrk 421, the bright soft X-ray emission may be a continuation of the synchrotron emission that is responsible for the radio, infrared, optical, and ultraviolet continuum. The lack of a smooth connection between the ultraviolet and X-ray continuum in 3C 446 suggests that the X-ray flux is produced a mechanism other than the synchrotron process, probably by the inverse Compton mechanism.

Fig. 4. The ultraviolet continuum of 1156+295 decreased rapidly during April 1981 following a dramatic flare in which it reached B = 13 mag. The spectral slope of 1.7 was preserved as the source dimmed.

Figure 5. Flux density variations at X-ray, ultraviolet,

optical, and radio frequencies for 3C 446 between December 1983 and June 1985. Rapid variations in the X-ray flux during December 1983 are not seen in the optical waveband. The ultraviolet and optical flux variations were identical and are similar to the long term variation of the X-ray emission. Variability at radio frequencies is slower and of lesser magnitude than at higher frequencies.

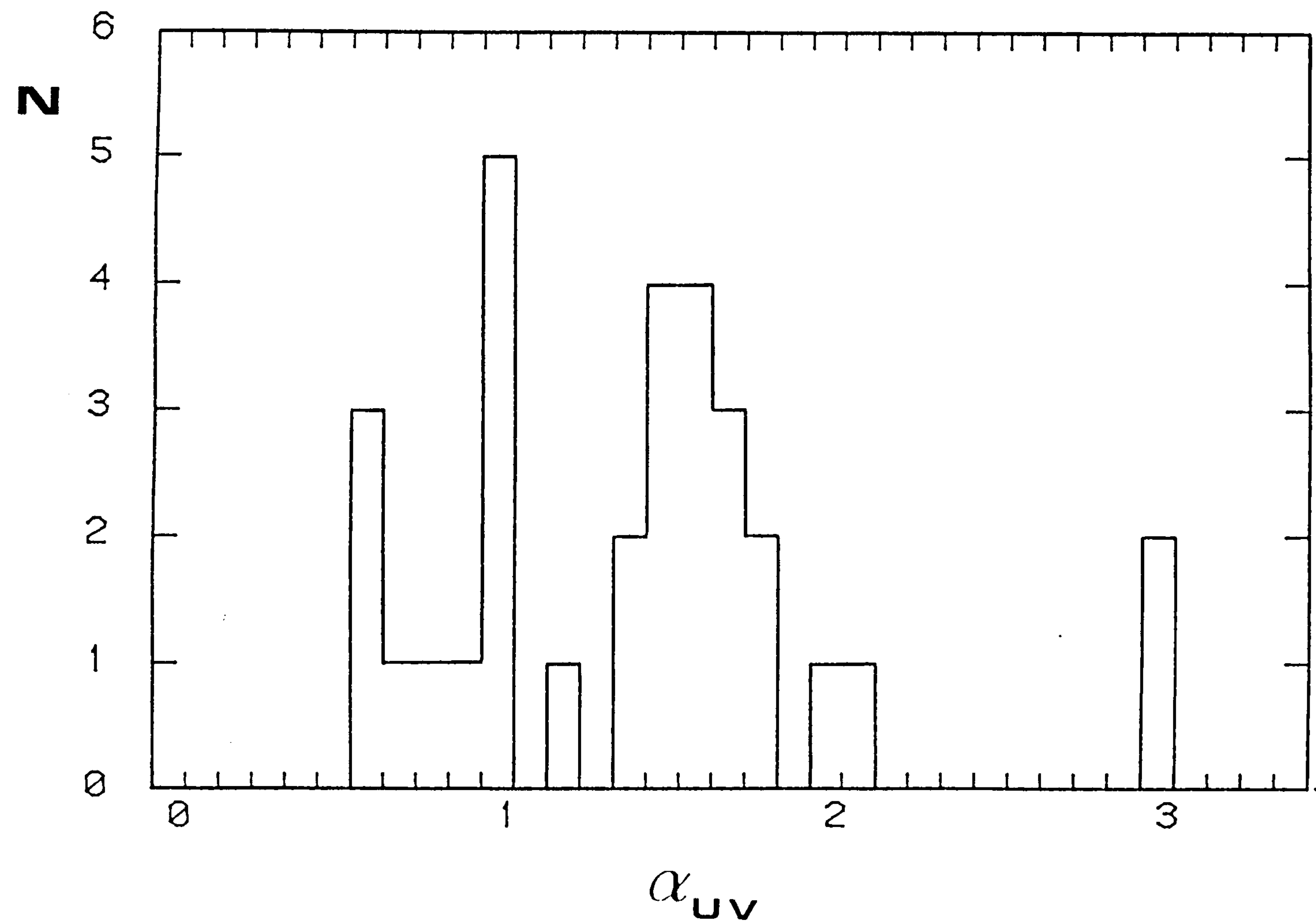
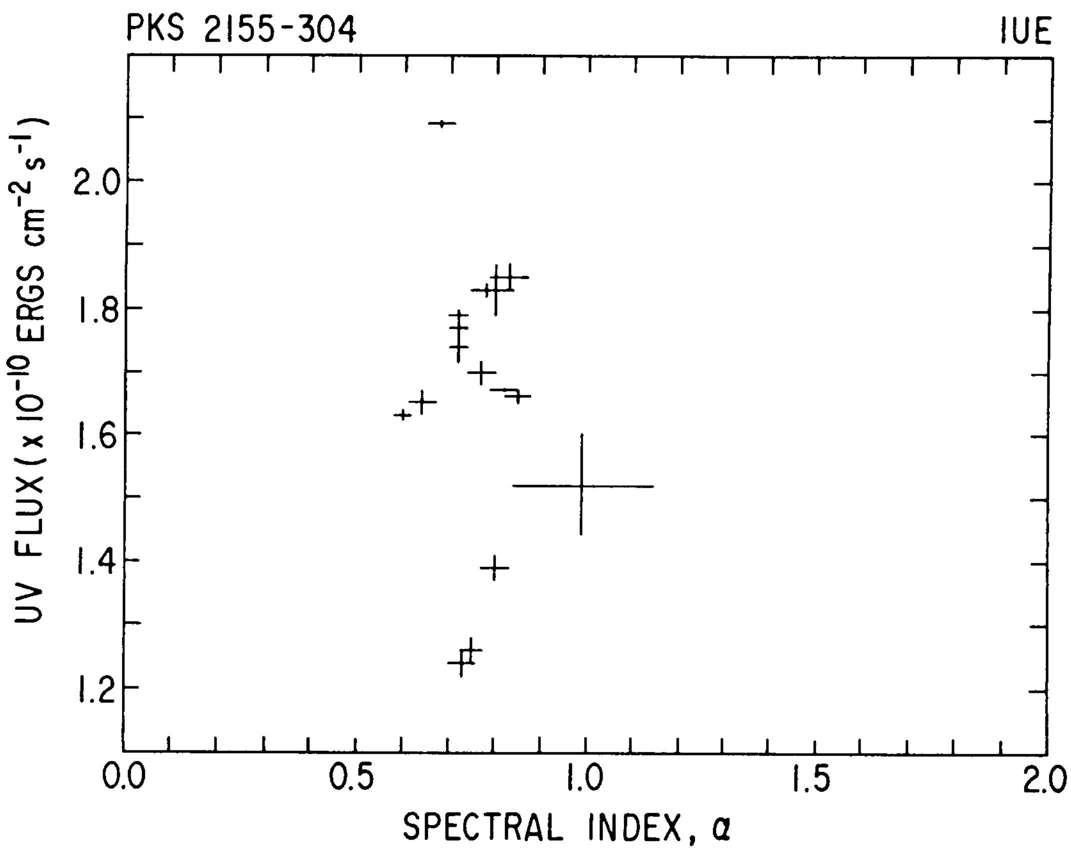
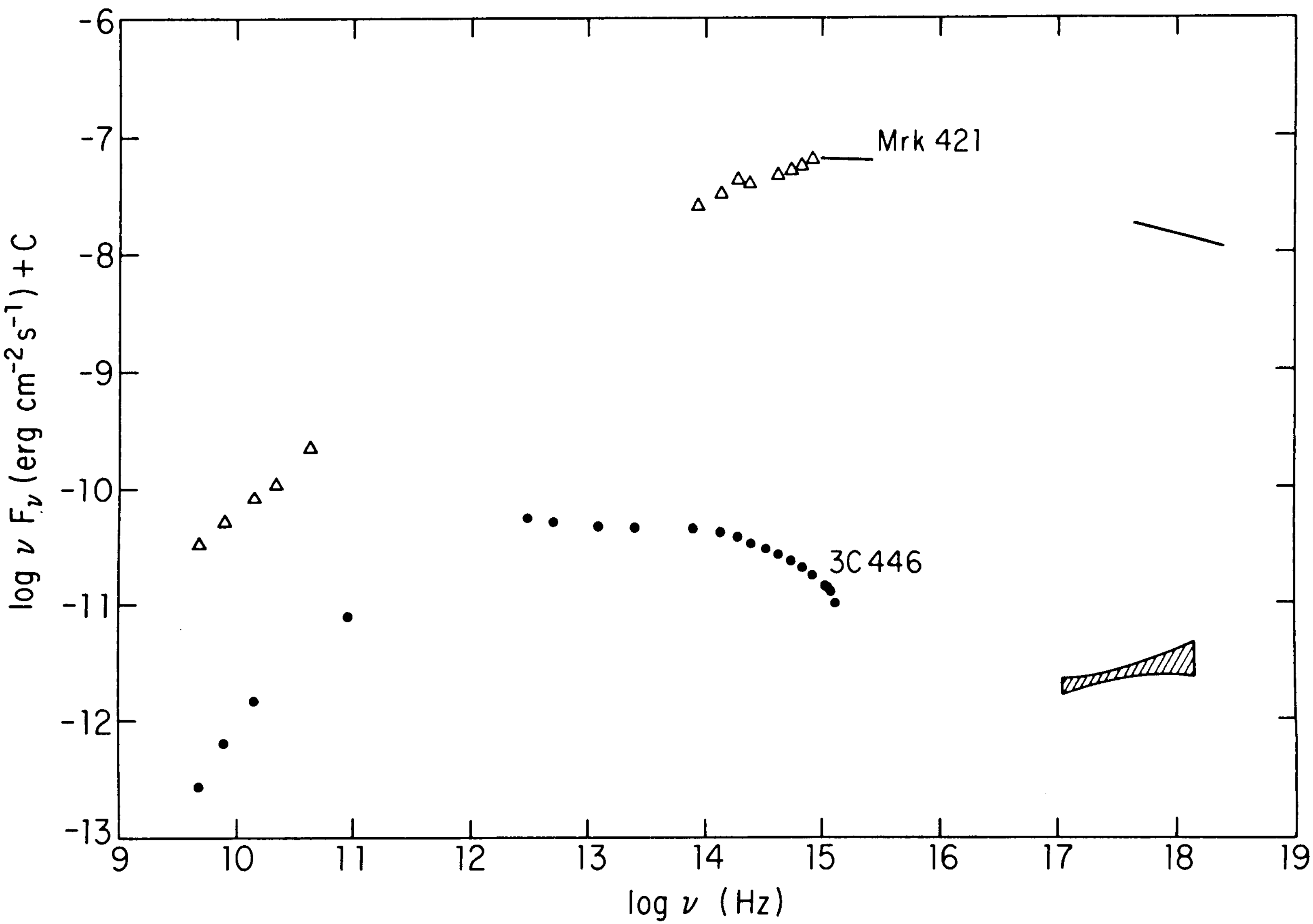


Fig 1


PKS 2155-304
IUE
UV FLUX (x 10^{-10} ERGS cm^{-2} s^{-1})
2.0
1.8
1.6
1.4
1.2
0.0
0.5
1.0
1.5
2.0
SPECTRAL INDEX, α



log ν F_ν (erg cm^-2 s^-1) + C
-6
-7
-8
-9
-10
-11
-12
-13
9
10
11
12
13
14
15
16
17
18
19
log ν (Hz)
Mrk 421
3C 446

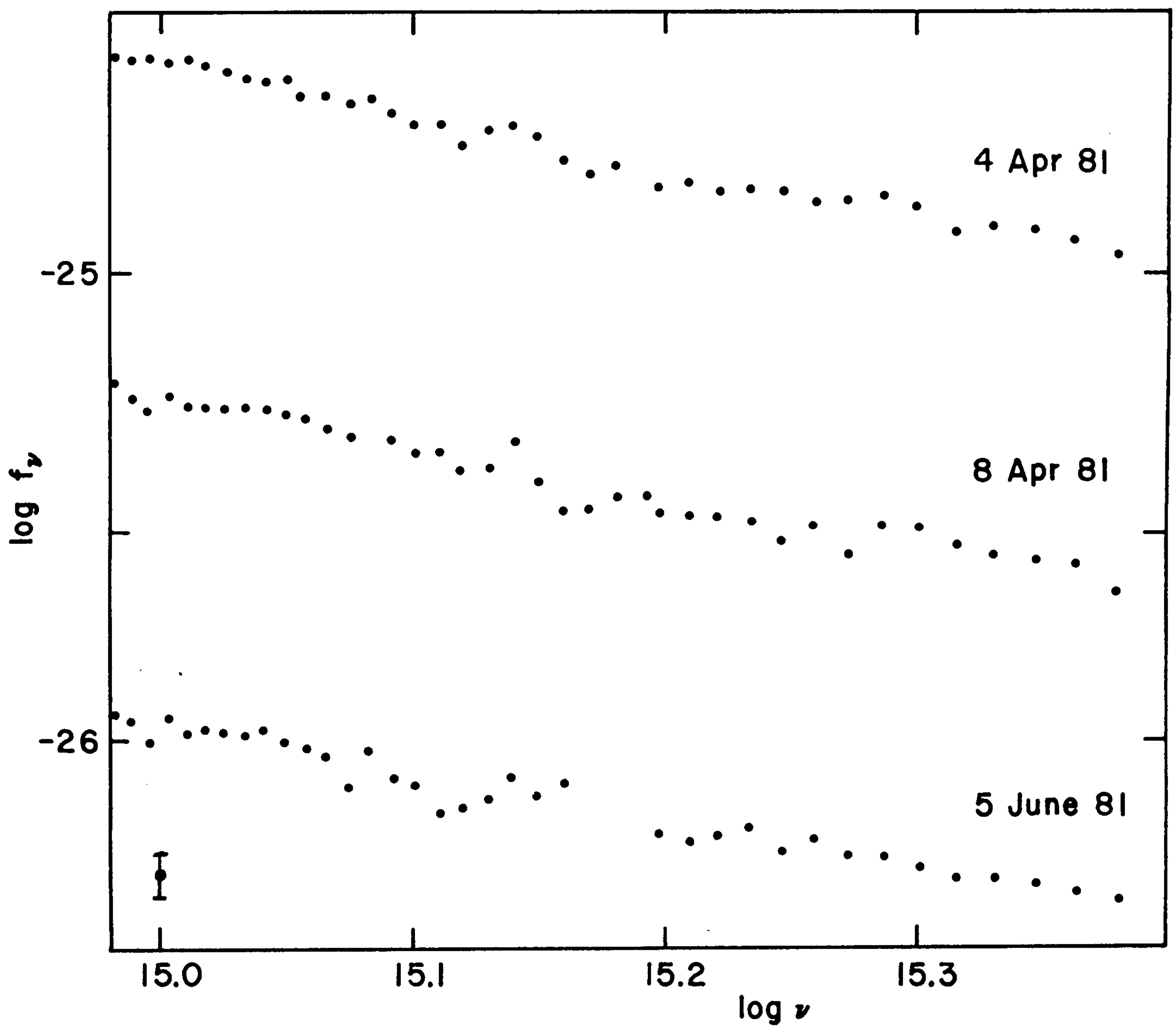
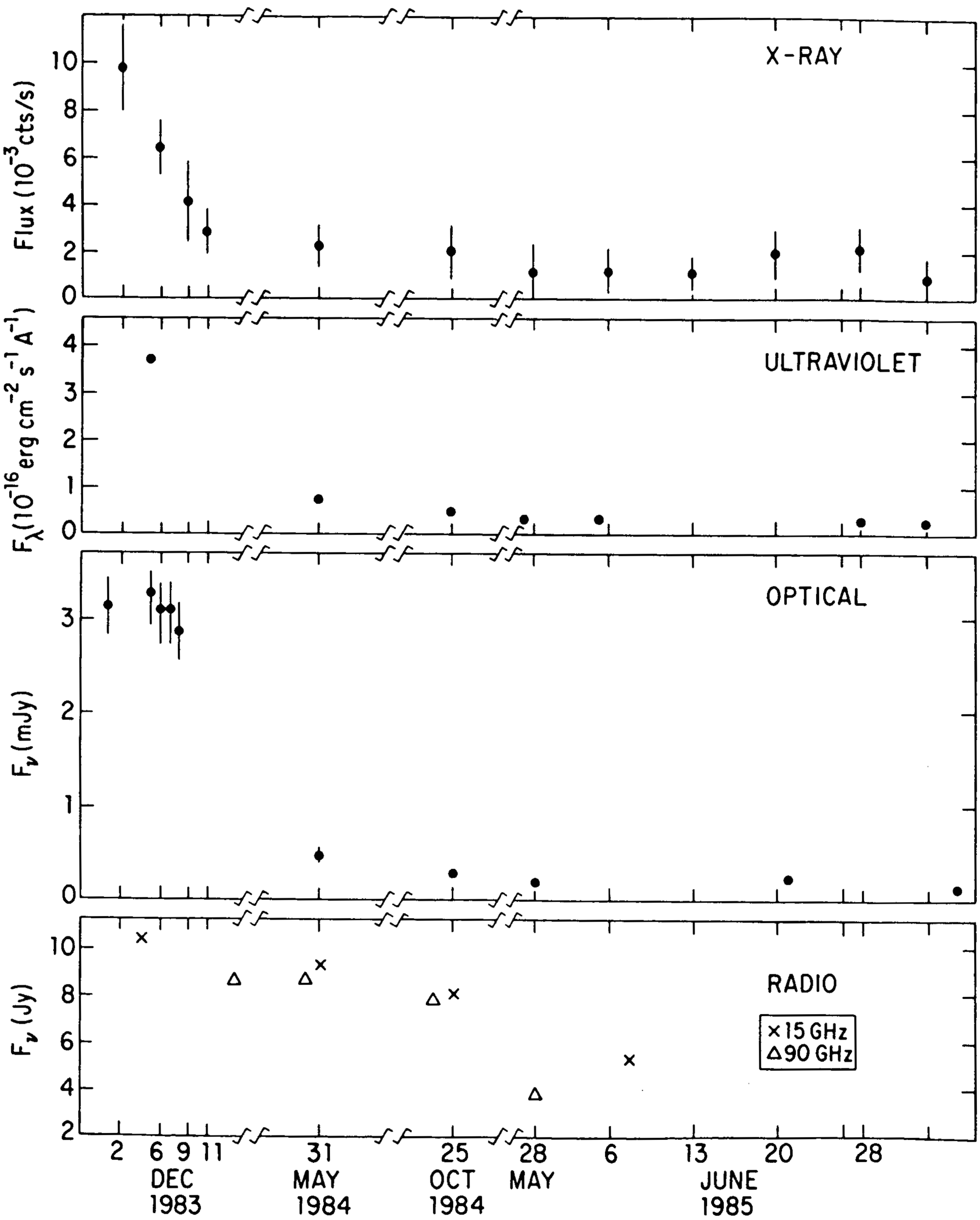


Fig 4


X-RAY
Flux (10^{-3} cts/s)
ULTRAVIOLET
F_λ (10^{-16} erg cm^{-2} s^{-1} A^{-1})
OPTICAL
F_ν (mJy)
RADIO
F_ν (Jy)
× 15 GHz
Δ 90 GHz
2 6 9 11
DEC
1983
31
MAY
1984
25
OCT
1984
28
MAY
6
13
JUNE
1985
20
28